A Real-Time SAR Processor using one-bit raw signal coding for SRTM

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Summary

The great success of the two SIR-C/X-SAR missions and the lack of global topographic data are the reasons at the basis of third Shuttle Radar Topographic Mission (SRTM). The mission is a joint program among NASA NIMA, DLR and the Italian Space Agency. The SRTM mission aims is to create a tri-dimensional topographic map of the Earth's surface 30 times as precise as the best global maps in use today.

The sophisticated mission technology is able to produce topographic maps with a level of detail never achieved before and a very good height precision.

The technique used, based on microwave instruments with a synthetic aperture radar, is a totally new concept in geodesy, the science that studies the morphology of planet Earth and measures its characteristics.

The mission has been also a great opportunity to test in an operational contest a innovative one bit processing chain operating in the pure time domain. The processor focuses the X-SAR signum coded raw data applying a quasi-phase preserving algorithm. The equivalent computing power is about 8,000 billions operations per second.

The processor architecture is such to comply with the continuous data flow coming from the instrument delivering a striped image.

Alenia Spazio, beside the responsibility with Dornier of the design and realisation of the X-band radar, also in this case under ASI contract, has designed and realised a complete ground station organised as a X-band data Processing Chain installed and operated at JPL site. This includes a Real-Time SAR processor, a comprehensive data management system and finally a topographic post-processing station.

Astonishing results have been produced both as single-bit focused SAR images and digital elevation models, also thanks to the advanced capabilities developed in last years at University Federico II of Naples one of the more active research institutions in this field.

Background

X-SAR, X band Synthetic Aperture Radar, was developed by Alenia Aerospazio for Italian Space Agency (ASI), as part of the joint Italian, German and US space Shuttle Radar Laboratory (SRL) program.

It was designed for integrated operation with the SIR-C Synthetic Aperture Radar developed by JPL as part of the same mission.

The instrument was successfully qualified and validated through two space shuttle missions in 1994, were its challenging imaging performance at X band were proven.

It was the first X-band SAR developed for spaceborne applications, and provided a significant contribution to improve the knowledge of multi-frequency SAR imaging in co-operation with the L/C band of SIR-C instrument.

New Features

X-IFSAR is a radar interferometer based on a couple of Synthetic Aperture instruments, that share the transmitting antenna while hold separate the receiving channels including antennas, RF sections and digital data handling subsystems.

The X-Band acquisition is guaranteed providing all weather operation and night/day imaging and topographic mapping of about 35% of the Earth surface.

The Italian Processing Chain operated in connection with X-IFSAR in Pasadena (CA) at the Jet Propulsion Laboratory NASA centre.

The direct down-linked data was available for processing and delivering first absolute DEM products together with auxiliary functions aimed to instrument in-flight calibration and performance monitoring.

The X-IFSAR Processing Chain employees a revolutionary real-time parallel processor based on a proprietary ASIC solution. Each of the 128 ASICs,

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developed using VHDL coding and Field Programmable Gate Array (FPGA) technology, endorses the Single Bit SAR coding and focusing algorithm, first conceived and analysed by the University of Naples "Federico II", Department of Electrical Engineering.

The Signum Code (SC) algorithm, together with state-of-the-art FPGA chip architecture, made the real-time operation possible, achieving full geometric resolution on SAR images and full height accuracy for DEM generation.

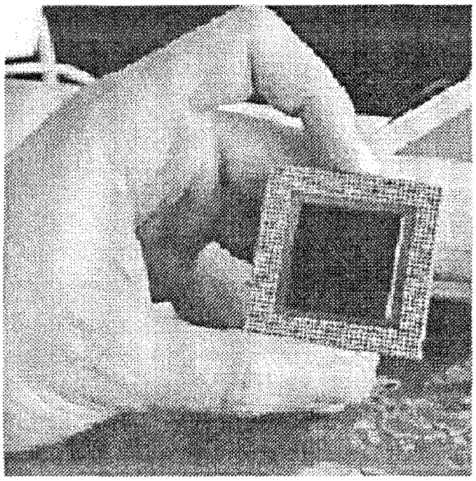

Figure 1 The TD Complex Correlator FPGA

Applications

X-IFSAR is derived from X-SAR whose primary application has been Earth surface imaging together with the study of the moisture connected to hydrology, geology, ecology and other disciplines.

The specific purpose of X-IFSAR is the measurement of ground height in order to deliver high resolution, high accuracy topographic maps all over the world. The planning of the 11-days SRTM mission constrained X-IFSAR to acquire about 35 % of the Earth surface within +/- 57° latitude boundaries.

The Italian Operational Processing Chain has been used within the mission-time frame for in-flight calibration purposes and absolute first product generation.

After SRTM conclusion, it has been installed at "Centro di Geodesia Spaziale" Matera – Italy – where all the SRTM data set has been available starting from November 1999. There the Processing Chain has been used for systematic fast product generation.

The comparison with the large data sets acquired during SRL missions in 1994 will also allow the observation of midterm geological process, soil erosion and deserts progression within a five years period.

The huge coverage granted during SRTM by X-IFSAR will allow once again the analysis of precipitation over tropical forest and ice properties and their variation and, finally, ocean large-scale dynamics.

Basic SC Arithmetic

The arithmetic operation that plays the central role in the novel SC data representation is the multiplication.

Given h and r two variables defined within the real field number (usually represented adopting the IEEE754 standard on conventional computer FPUs), two new variables can be associated as defined here below

$$h \rightarrow \hat{h} = \begin{cases} +1 & h > 0 \\ -1 & h < 0 \end{cases}$$

and

$$r \rightarrow \hat{r} = \begin{cases} +1 & r > 0 \\ -1 & r < 0 \end{cases}.$$

The new variables, generated by means of a hard quantization, also belong to the real number field, but they can assume only two values.

Now the new variables can be re-coded using a more appropriate representation that accounts for true possible states. The binary representation is immediate.

Let's H and R be the codes corresponding to $\hat{h}$ and $\hat{r}$:

$$\hat{h} \rightarrow H = \begin{cases} 1 & \hat{h} = +1 \\ 0 & \hat{h} = -1 \end{cases}$$

and

$$\hat{r} \rightarrow R = \begin{cases} 1 & \hat{r} = +1 \\ 0 & \hat{r} = -1 \end{cases}$$

The binary coding of hard quantized variables H and R is named ***Signum Coding*** shortened in this frame with the symbol ***SC***.

Now let's examine how the signum coding works on arithmetic multiplication.

The h by r product generates the results s that can be represented using binary coding too.

It can be shown that the value of S, the SC of s, obtained by means of the negation of an exclusive OR between H and R, is exactly equal to the value got applying SC on the hard quantization of $s = h \cdot r$.

In term of mathematics this property can be written as:

$$\hat{s} = \hat{h} \cdot \hat{r} \Rightarrow S = \overline{R \otimes H}$$

which can be verified case by case looking into Table 1, where S, computed in the two equivalent ways, are systematically compared.

$\hat{r}$	$\hat{h}$	$\hat{r} \cdot \hat{h}$	R	H	$\overline{R \otimes H}$	$\hat{s}$
+1	+1	+1	1	1	1	+1
+1	-1	-1	1	0	0	-1
-1	+1	-1	0	1	0	-1
-1	-1	+1	0	0	1	+1

Table 1 – Real/Boolean relations for multiplication

If the True State Counter (TSC), or "1" occurrences counter, is defined using the symbol

$$\left\|S_j\right\|_{j:CNT}^{\{\cdot\}} := \begin{array}{l} \textit{counts the number of " } S_j = 1 \textit{"} \\ \textit{occurrences while } j \textit{ varies} \end{array}$$

the sum of products s_j can be written using the equivalent SC coding

$$\sum_{j=1}^{N} \hat{s}_j = 2 \cdot \left\|S_j\right\|_{j:CNT}^{1,N} - N$$

where N, the number of added elements s_j, acts as a bias. N is sometimes called "magic number".

Signum Code SAR Focusing Algorithm

Here the SAR processing algorithm based on the SC raw data representation is detailed as implemented within the X-SAR Processing Chain.

The time domain operation used for SAR focusing is the bi-dimensional correlation, performed using mono-dimensional correlation followed by results addition. This correlation is defined in the complex number field and can be decomposed into four real number field correlations.

Therefore the basic function is the real correlation, which is susceptible of signum coding representation.

Real Correlation

Let $r(*,*)$ be the input complex data matrix built of the aligned raw data radar echoes, and $h(*,*)$ be the complex bi-dimensional space-varying holographic SAR reference function.

The derived measurement $s(*,*)$ of local ground whet reflectivity can be computed in the native time/space domain as the correlation product :

$$s(i,j) = \sum_{p=1}^{Nr} \sum_{q=1}^{Na} r(i+p, j+q) \cdot h_{i,j}(p,q).$$

The space varying dependence of $h_{i,j}(p,q)$ is depicted by the i and j indexes. The hard quantization transforms the expression of $s(i,j)$ into

$$\hat{s}(i,j) = \sum_{p=1}^{Nr} \sum_{q=1}^{Na} \hat{r}(i+p, j+q) \cdot \hat{h}_{i,j}(p,q).$$

It is not relevant now how the $\hat{s}(i,j)$ and $s(i,j)$ expressions differ, because the theoretical SAR focusing performance is not a matter of interest here.

If the equivalence property of the sum products is applied, the $\hat{s}(i,j)$ can be immediately evaluated employing the SC representation and getting the relationship

$$\hat{s}(i,j) = 2 \sum_{p=1}^{Nr} \left\| \overline{R(i+p, j+q) \otimes H_{i,j}(p,q)} \right\|_{q:CNT}^{1,Nq} - N_p N_q$$

The bi-dimensional count operation is exploited into the sum in one dimension of mono-dimensional counts in the other one.

Complex Correlation

The complex correlation is similar to the real one analysed in the previous section. The mathematical definition of it is exploited by the following equation

$$s(i,j)=\sum_{p=1}^{Nr}\sum_{q=1}^{Na} r(i+p,j+q)\cdot h^{*}_{i,j}(p,q)$$

where $h_{i,j}(p,q)$, $r(i,j)$ and $s(i,j)$ are complex numbers instead of real numbers.

Note that the reference function $h_{i,j}(p,q)$ shall be conjugated in order to express a full significant correlation.

The complex multiplication between two complex numbers can be reduced into a set of four real multiplications and their proper combination for generation the real and imaginary part.

Given A and B the signum code representations of two complex numbers where, A^{Re}, B^{Re}, A^{Im} e B^{Im} stay for the four components, the complex multiplication of A by B* (* signifies complex conjugation function).

$$C=A\cdot B^{*}$$

is equivalent to the combination of six real field operations

$$C\rightarrow\begin{cases}C^{Re}=A^{Re}\cdot B^{Re}+A^{Im}\cdot B^{Im}\\ C^{Im}=-A^{Re}\cdot B^{Im}+A^{Im}\cdot B^{Re}\end{cases}$$

This relates to the complex product only. If the complex addition is introduced, the sum of complex products

$$c=\sum_j a_j\cdot b_j^{*}$$

can be translated in the real field according to the scheme here below

$$c\rightarrow\begin{cases}c^{Re}=\sum_j a_j^{Re}\cdot b_j^{Re}+\sum_j a_j^{Im}\cdot b_j^{Im}\\ c^{Im}=-\sum_j a_j^{Re}\cdot b_j^{Im}+\sum_j a_j^{Im}\cdot b_j^{Re}\end{cases}$$

Now, by applying the discussed rules and dividing by 2 (which does not break the generality of this property), the SC representation S of s can be computed as

$$C=\frac{c}{2}\rightarrow\begin{cases}C^{Re}=\left\|\overline{A_j^{Re}\otimes B_j^{Re}}\right\|_{j:CNT}^{1,N}+\left\|\overline{A_j^{Im}\otimes B_j^{Im}}\right\|_{j:CNT}^{1,N}-N\\ C^{Im}=-\left\|\overline{A_j^{Re}\otimes B_j^{Im}}\right\|_{j:CNT}^{1,N}+\left\|\overline{A_j^{Re}\otimes B_j^{Im}}\right\|_{j:CNT}^{1,N}\end{cases}$$

Note that the imaginary part C^{Re} only requires the bias compensation due to the presence of positive counters. On the other hand the biases of the two C^{Im} components compensate each other.

For the purposes of the SAR focusing application, the by 2 division does not break the validity of the property.

Non space-varying SAR focusing

The ideal SAR focusing scheme has been employed that fully respects the intrinsic space-variance of SAR acquisition system. In fact the the reference correlation function $h_{i,j}(p,q)$ depends on the raw data sample position through i and j.

The implementation of full space-variant filter is not realistic and would lead to an extremely complex design resulting not compatible with real-time architecture and run.

The relationship that determines the translation from raw data to focused image shall be therefore simplified in some way.

Keeping the same meanings for $r(*,*)$ and $s(*,*)$ an alternate relation is derived that expresses $s(i,j)$ as

$$s(i,j)=\sum_{p=1}^{Nr}\sum_{q=1}^{Na} r(i+p,j+q)\cdot h_K(p,q)$$

where $h_K(p,q)$ is frozen in connection with a limited number of K values (K from 1 to 5 are reasonable) in such a way to assume a piecewise constant reference function. The validity region of each filter make the processing act as 'unfocused'.

The requirement baseline requests for one single correlation filter all over the swath that shall be matched in correspondence of the swath centre. The azimuth focusing degradation implied by that choices directly proportional to the swath width where the single filter operates a space-invariant correlation.

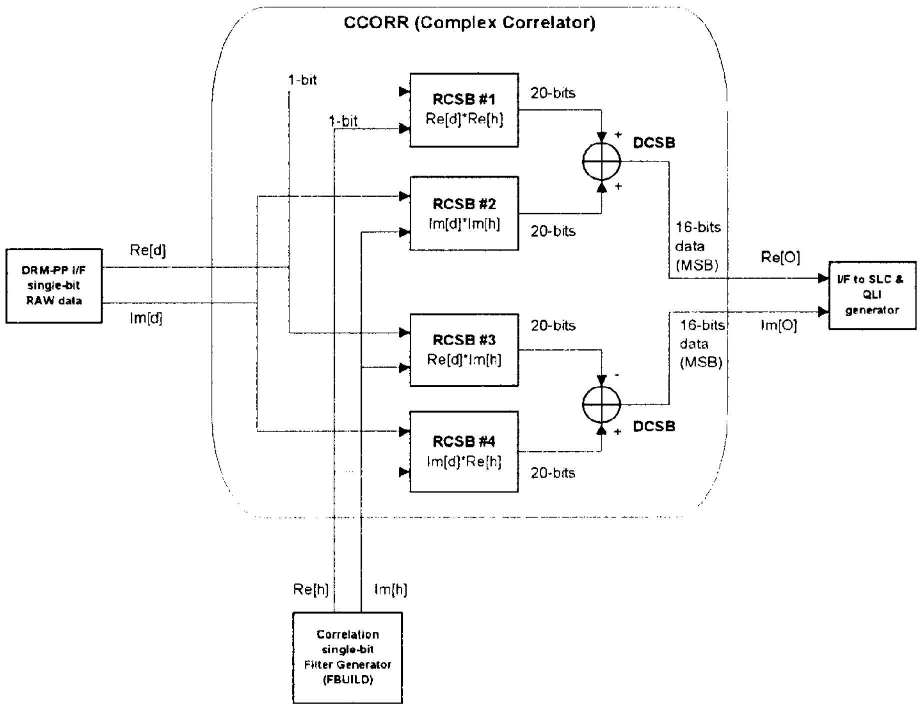

Figure 2 Time Domain Complex Correlator Architecture

Fast Filter Evaluation

If r_{CS} is the centre swath range, that is the distance between the antenna phase center and the swath center, the Doppler rate μ_A induced by the effective relative motion is given by:

$$\mu_A = -\frac{2 \cdot V_{proc}^2}{\lambda \cdot r_{CS}}$$

where the negative sign is due to the physical change of radar-to-target distance during SAR motion.

The azimuth quadratic phase excess $\Phi_{Aq}(t)$, as function of flight time t computed at swath center, is then defined as

$$\Phi_{Aq}(t) = \pi\mu_A(t - t_0)^2 \quad with \ |t - t_0| < \frac{T_A}{2}$$

where t_0 is the flight time over a specified target placed at swath center and T_A is the coherent integration time. t is the flight time.

This is an exact expression at swath centre only and should be corrected for any other range position. The assumption of using a single reference filter consists in extending the validity of this quadratic phase shape to all ranges within the swath.

The total azimuth phase excess shall include also the linear term induced by the Doppler centroid, physically due to a slight skew in acquisition geometry. If f_{Dc} is the Doppler centroid frequency the azimuth linear phase term is given by

$$\Phi_{Al}(t) = 2\pi \cdot f_{Dc}(t - t_0) \quad with \ |t - t_0| < \frac{T_A}{2}$$

The range quadratic phase is instead determined by the chirp pulse bandwidth and duration. If Tp is the pulse

duration and Bp its bandwidth, the chirp rate μ_R is simply given by the ratio

$$\mu_R = \frac{B_p}{T_p}$$

then the range quadratic phase $\Phi_R(\tau)$, as function of echo fast time τ, can be computed as

$$\Phi_R(\tau) = \pi\mu_R(\tau - \tau_0)^2 \quad with \ |\tau - \tau_0| < \frac{T_p}{2}$$

where τ_0 is the centre of the chirp pulse.

The correlation filter $h_K(p,q)$ (this is not the signum coded filter but the full dynamic one) is defined over the 2D domain determined by the range axis (p index samples) and the azimuth axis (q index samples).

The relation between range index p and echo fast time τ is defined by the sampling frequency f_S

$$\tau_p = \frac{p}{f_S}$$

while the relation between the azimuth index q and the flight time t is determined by the pulse repetition frequency (PRF) as

$$t_q = \frac{q}{PRF} + t_{REF}$$

where t_{REF} is arbitrary and can be ignored without lacking of generality.

Assuming the following ranges for p and q:

p = 1, 2, ..., N_r

q = 1, 2, ..., N_a

the time centres t_0 and τ_0 are assumed in correspondence of

$$t_0 = \frac{1+N_a}{2 \cdot PRF}$$

and

$$\tau_0 = \frac{1+N_r}{2 \cdot f_S}$$

so that the total phase $\phi(t,\tau)$ over the filter, that can be computed in the 2D continuous domain as

$$\phi(\tau,t) = \phi_{Aq}(t) + \phi_{Al}(t) + \phi_R(\tau)$$
$$with \ |\tau - \tau_0| < \frac{T_p}{2} \ and \ |t - t_0| < \frac{T_A}{2}$$

is re-written according the expression

$$\bar{\phi}(p,q) = \bar{\phi}_{Aq}(q) + \bar{\phi}_{Al}(q) + \bar{\phi}_R(p)$$
$$with \ p = 1,..,N_r \ and \ q = 1,..,N_a$$

where

$$\bar{\phi}_{Aq}(q) = \pi\frac{\mu_A}{PRF^2}\left(q - \frac{1+N_a}{2}\right)^2$$

$$\bar{\phi}_{Al}(q) = 2\pi \cdot \frac{f_{Dc}}{PRF}\left(q - \frac{1+N_a}{2}\right)$$

$$\bar{\phi}_R(p) = \pi\frac{\mu_R}{f_S^2}\left(p - \frac{1+N_r}{2}\right)^2.$$

From the total phase $\bar{\phi}(p,q)$ the real and imaginary parts of the correlation filter $h_K(p,q)$ can be computed as:

$$h_K^{\mathrm{Re}}(p,q) = \cos[\bar{\phi}(p,q)]$$
$$h_K^{\mathrm{Im}}(p,q) = sen[\bar{\phi}(p,q)]$$

which are the full dynamic versions of the correlation filter required by Signum Code SAR focusing algorithm.

The Signum Code version can be immediately derived. Anyway, without computing the trascendent functions,

it is possible to generate the signum of cosine and the signum of sine using the simple verification rule based on the phase normalization.

A normalized phase Ψ is associated to the true phase $\bar{\phi}$ by means of:

$$\Psi = \mathrm{mod}\left[\frac{2\bar{\phi}}{\pi}, 4\right]$$

that furnishes Ψ in the range [0,4[. Then the sine signum S_{sine} and cosine signum S_{cosine} are immediately obtained looking for the integer value of Ψ achieving at the end:

$$Z = \mathrm{int}(\Psi) \rightarrow \begin{cases} S_{cosine} = +1 \quad S_{sine} = +1 \quad if\ Z = 0 \\ S_{cosine} = -1 \quad S_{sine} = +1 \quad if\ Z = 1 \\ S_{cosine} = -1 \quad S_{sine} = -1 \quad if\ Z = 2 \\ S_{cosine} = +1 \quad S_{sine} = -1 \quad if\ Z = 3 \end{cases}$$

System Operation

The system operation was based on joint operation of an On-Board Segment, including the SAR sensor, with the Ground Segment, including the necessary equipment for mission planning, control and data image and DEM processing.

The On-Board segment includes the two X-band antennas (12 m and 6 m azimuth apertures), integrated with the C-band antennas, the RF and digital subsystems for interferometric radar operations. Digital data was formatted and stored on-board and a fraction (~2%) was down-linked to the Jet Propulsion Laboratory.

The Italian Processing Chain for X-IFSAR was supported by the mission and sensors planning operators. Most of instrument parameters, significant for final image and DEM performance, was monitored in conjunction with the German and US Ground Segments.

The X-IFSAR Processing Chain supplied the acquisition and monitoring of housekeeping data received from the sensor via the high-rate bit-multiplexed channels, as well as the real-time focusing processing of received scientific data through SAR images generation. All bit-stream synchronisation was performed using latest hardware and software available technologies.

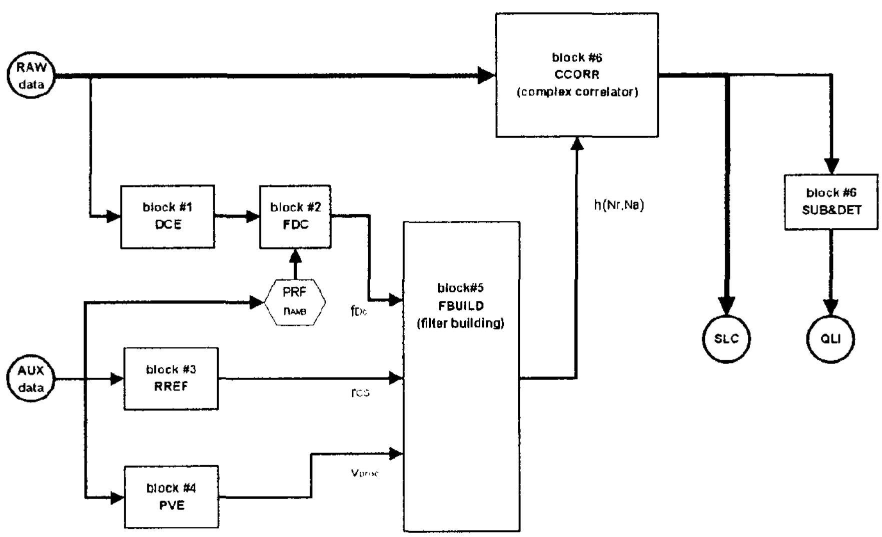

Figure 3 Overall SAR focusing SC algorithm block diagram implementation

Key Technologies

The emphasis of X-SAR development was put on application of the latest available space qualified technologies.

Now the technologies employed within the advanced X-IFSAR Italian Processing Chain are the key through the incoming Italian Space Programs, such as COSMO and SAR2000, that will benefit of the drawback of the developments and results achieved in the frame of SRTM program.

The present SAR processor is a machine that sizes as large as one VME crate cabinet (8 boards) that, thanks to the acquired know-how, will be miniaturised down to a single double-Europe card and few tens of Watt power supply.

These feature and specifications in terms of envelope, mass and power enables the on-board implementation of the Signum Code SAR processing technique which is seen now as the switch-on gate toward new applications of spaceborne SAR instruments addressed to a larger base of users.

This is the key relevance of the Italian participation to SRTM where SRL experience and academic invention has been exploited.

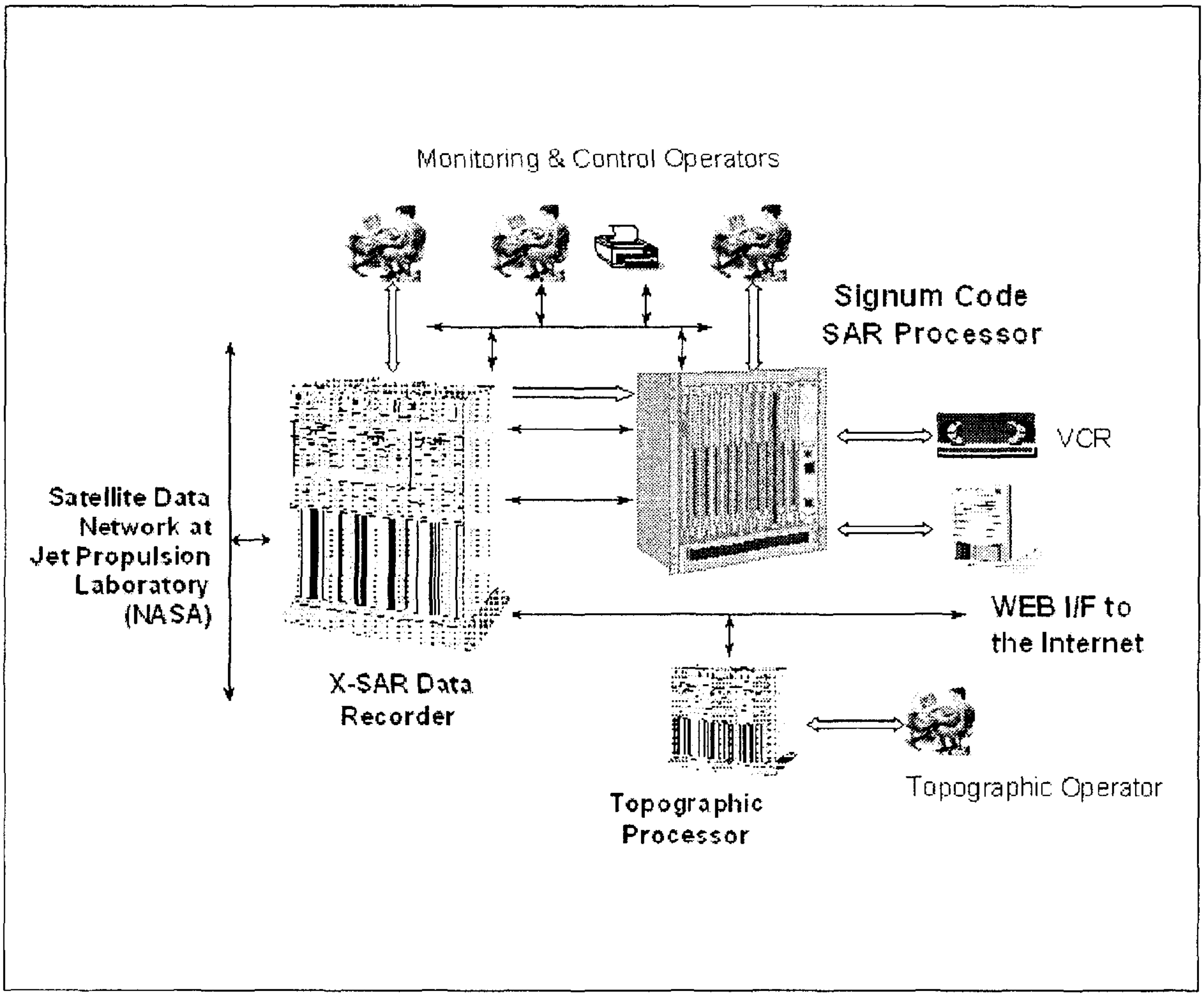

Figure 4 Overall Processing Chain Architecture as implemented at JPL site

Here are listed main specifications of the X-SAR Processing Chain components.

SAR Processor

implementation	Full-custom
SAR Processor Algorithm	Time-Domain Signum Code
Operation Capability	Real-Time
Architecture	SIMD
CPU Technology	FPGA / BGA
Number of CPUs	128
Clock Frequency	30 MHz
Equivalent Computing Power	~ 6,500,000 Mops
Master Controller	Motorola 68060
RT Operating System	OS9k
Input I/F: raw data auxiliary command	IEEE 1284 RS232C VME-PCI bridge
Output Interface	Fast Ethernet
Local Storage	63 GByte
Recording Autonomy	35 minutes

Chain Controller

Host Computer	IBM-PC
Platform Architecture	Intel PII @450 MHz
Operating System	NT 4.0
Control Environment	LabView 5TM
Local Control	full
Remote Control	operations
Thermal Control	on 128 CPUs
Fan Control	VME fans
I/O Control Interface	VME
RT Image Data Display	Viper550-TNT
On-Screen Resolutions	800x600 1280x1024 1600x1200
VCR	PAL (VGA)
System Printer	InkJetTM
Photographic Support	NP1600

Data Management Service

Host Computer	SUN E450 WS
Disk Storage	117 GByte
RAM Memory	1 GByte
CPUs	4 x 400 MHz - UltraSPARC
I/O Interfaces	Fast Ethernet
Tasks on X-SAR raw data	Synchro-Deformat - DQA/PE
Service Capability	60 minute/day
Network Services	FTP Server & WEB Server

Topographic Processor

Host Platoform	SUN E450 WS
Disk Storage	33 GByte
RAM Memory	512 MByte
CPUs	4 x 300 MHz - UltraSPARC
I/O Interface	Fast Ethernet
Products	Fringes & DEM
Processing Capability	1 DEM / 2 hours
Algorithm & S/W Source	University of Naples

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